Tropical Cyclone Structure and Intensity Change Related to Eyewall Replacement Cycles and Annular Storm Formation, Utilizing Objective Interpretation of Satellite Data and Model Analyses

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LONG-TERM GOALS

This project aims toward increasing our understanding of the dynamics of secondary eyewalls in tropical cyclones and our ability to forecast their formation and associated intensity changes. This is being accomplished through a synergistic combination of theoretical, empirical, and numerical modeling approaches. We expect to apply our results to the construction of objective algorithms that will be transitioned to operations to provide forecasters with new tools for improved forecasting of tropical cyclone structure and intensity.

OBJECTIVES

1) Elucidate the internal vortex dynamics associated with secondary eyewall formation (SEF) with a unique combination of basic theory, idealized models, and full-physics models.

2) Identify and quantify the environmental factors related to SEF through application of reanalysis fields and satellite imagery.

3) Construct objective algorithms to diagnose SEF (and associated intensity changes) in real-time.

APPROACH

We're following a multi-pronged approach that incorporates basic theory, idealized modeling, full-physics modeling, and empirical/statistical analyses. Guidance for the empirical/statistical analyses is

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14. ABSTRACT
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derived from the basic theory and idealized modeling results. The results of the empirical/statistical analyses then provide guidance for a systematic suite of full-physics modeling experiments. Our empirical/statistical approach involves composite analyses and Principal Component Analyses (PCA) of storm-centered environmental fields and satellite imagery. We are developing an objective classification scheme that diagnoses and forecasts SEF. The classification algorithm is being developed in a Bayesian framework. The idealized modeling part of this work has utilized a diagnostic model based on the Eliassen transverse circulation model. In future work the diagnostic analyses using the Eliassen model will be extended to unsteady dynamics using a time-dependent, nonhydrostatic model of symmetric vortex dynamics. The full-physics modeling part of this project will involve idealized simulations of tropical cyclones designed to reproduce eyewall replacement cycles and related processes.

WORK COMPLETED

Dr. Christopher Rozoff joined this project in May 2007 as a new post-doctoral hire, and has been highly productive in the past 5 months since then. The Eliassen model has provided very useful information about the physics of tropical cyclone eyewall replacement and a paper documenting these results has been submitted to the Quarterly Journal of Royal Meteorological Society.

Matthew Sitkowski is a new Ph.D. candidate who joined our group in mid-June 2007, and he has recently completed the construction of a global sample of cases of SEF and eyewall replacement. This required a careful analysis of thousands of microwave satellite images, radar images, and text reports. We are now constructing an eyewall replacement climatology from this large global sample. This will be the first such climatology ever constructed for this important process.

Dr. David Nolan has been using the Weather Research and Forecasting Model (WRF) to simulate tropical cyclones for the past five years. While the WRF model easily ingests real data as initial and boundary conditions from either global forecast models or from reanalyses, it is surprisingly difficult to initialize with idealized (hypothetical) initial and boundary conditions for research purposes. Over the last year, Dr. Nolan has developed a set of modified WRF codes that allows for the prescription of arbitrary initial cyclones in idealized environments, with user-defined mean flow and mean wind shear. Initial testing has shown that tropical cyclones of a wide variety of structures and behaviors can be simulated. We intend to use the idealized modeling system to study eyewall replacement cycles in full detail.

RESULTS

a) Theory and idealized modeling results

The use of idealized physical models has historically proved successful in revealing the fundamental underpinnings of complex physical phenomena. While tropical cyclones are inherently complex in their vast spectrum of physical scales and processes, models that isolate important underlying structures from these complex systems often promote an improved comprehensive understanding. An idealized approach can often yield enlightening solutions that unambiguously address the mechanics of a tropical cyclone.

Among the most successful idealized approaches in tropical cyclones research has been the investigation of balanced, axisymmetric dynamics in tropical cyclones. While this approach has

demonstrated remarkable advancements in our overall understanding of tropical cyclones, we restrict our current focus on its application to the outstanding forecasting challenge of concentric eyewalls and rapid intensity change. Based on a transverse circulation equation adapted from the classic result derived by Eliassen (1952), Shapiro and Willoughby (1982) suggested a plausible mechanism for eyewall contraction, where contraction is interestingly a direct function of inertial stability. Willoughby et al. (1982) exploited this vortex model further to explain their landmark observational analysis of eyewall replacement cycles. Willoughby et al. found that the situation of two concentric eyewalls creates hostile conditions for the inner eyewall, since a component of the subsidence induced by the outer ring decreases low-level inflow at radii within the outer ring. This aspect concerning the presence of an outer eyewall implies a decrease in low-level, radial angular momentum and, presumably, moist entropy fluxes into the inner eyewall. Therefore, we have a potential mechanism to explain the commonly observed decay of an inner eyewall. Since then, numerous publications have hypothesized about the role of suppressive subsidence, forced by an outer eyewall, upon an inner eyewall. Such hypotheses include a direct and/or an indirect impact, where the indirect impact is the adiabatic compressional warming and drying associated with subsidence. More sophisticated models that include microphysics and a planetary boundary layer have suggested that, in the moat between two eyewalls, there is a competition at low levels between downward advection of low entropy air and the upward turbulent flux of high entropy air from the sea surface, where the low entropy air wins the competition (e.g., Hausman 2001). Despite these advances in the realm of axisymmetric cyclone dynamics, our recent research efforts, summarized in what follows, suggest a deeper understanding of eyewall replacement cycles can be gained from further analysis of Eliassen's classic transverse circulation equation.

Our current approach closely follows the methodology of Schubert et al. (2007) used to study eye dynamics. Assuming a barotropic vortex, they derived an analytical solution of the Eliassen transverse circulation equation for a three-region approximation of an unforced central eye region of elevated inertial stability, an intermediate region of enhanced diabatic heating and elevated inertial stability, and an unforced far-field of low inertial stability. In our application, five regions are constructed to represent an eye, inner eyewall, moat, outer eyewall, and the far-field. The two eyewalls contain realistically prescribed diabatic heating, where the area averaged diabatic heating is constrained to a constant value consistent with microwave-derived precipitation measurements. Analytical solutions to the five-region model then describe the secondary circulations associated with a double eyewall structure. Flight-level data collected during a phase of concentric eyewalls in Hurricane Frances (2004) are compared with our analytical solutions. A wind profile is prescribed to approximate the observed profile (Fig. 1a). The diagnosed radial structure of the vertical motion field associated with our parameterized wind profile and double eyewall diabatic forcing is indicated as the solid curve in Fig. 1b. Subsidence is diagnosed within the eye, moat, and far-field, where far-field subsidence is much weaker than downward motion in the eye and moat. Since our model is linear, we can unambiguously determine the contributions of each eyewall to the secondary circulation. Subsidence in the eye is almost entirely due to diabatic heating in the inner eyewall, while subsidence near the center of the moat is equally a result of diabatic heating in the inner and outer eyewalls. From Fig. 1b it is also apparent that each eyewall has the effect of suppressing the other, but that the effect is essentially mutual and quite small. Thus, the oft-cited hypothesis that subsidence from the outer eyewall directly suppresses the inner eyewall is not supported by these results. Figure 1c shows the temperature tendencies implied from solutions to the transverse circulation equation and the observed temperature and dewpoint temperature profiles associated with the flight-leg in Fig. 1a. The radial structure of the temperature tendencies closely matches the structure of the observed temperature

profile. The flight-level observations of the double eyewall structure indicate a warm core inside the outer eyewall, with pronounced temperatures within and adjacent to the inner eyewall.

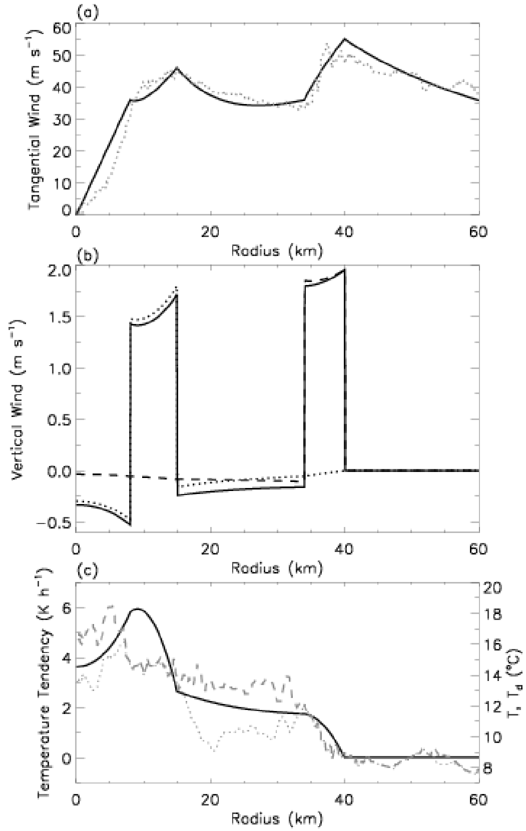

Figure 1. (a) Observed (dotted) and idealized (solid) tangential wind v(r) (m s^{-1}) profiles at 700 hPa for Frances between 2117 and 2126 UTC, 30 August 2004. (b) Radially-dependent part of log-pressure vertical velocity (m s^{-1}), due to the inner eyewall (dotted line), the outer eyewall (dashed line), and total vertical motion (solid line). (c) Observed temperature (dashed, ^{o}C), observed dewpoint temperature (dotted, ^{o}C), and the radially-dependent part of the temperature tendency (solid, K h^{-1}).

It is also of interest to investigate the evolution of the solutions to our transverse circulation equation as an eyewall replacement cycle progresses. First, noting that an outer eyewall will eventually triumph over an inner eyewall, we can study the impact of shifting diabatic heating from the inner to the outer eyewall. Three selected diabatic heating distributions are chosen (Fig. 2a), where the area-averaged diabatic heating remains fixed. This result shows that as diabatic heating shifts toward the outer eyewall, the warming within the eye, inner eyewall, and moat decreases. Thus, as heating shifts from the inner to outer eyewall, the ability of a tropical cyclone to build its warm core decreases.

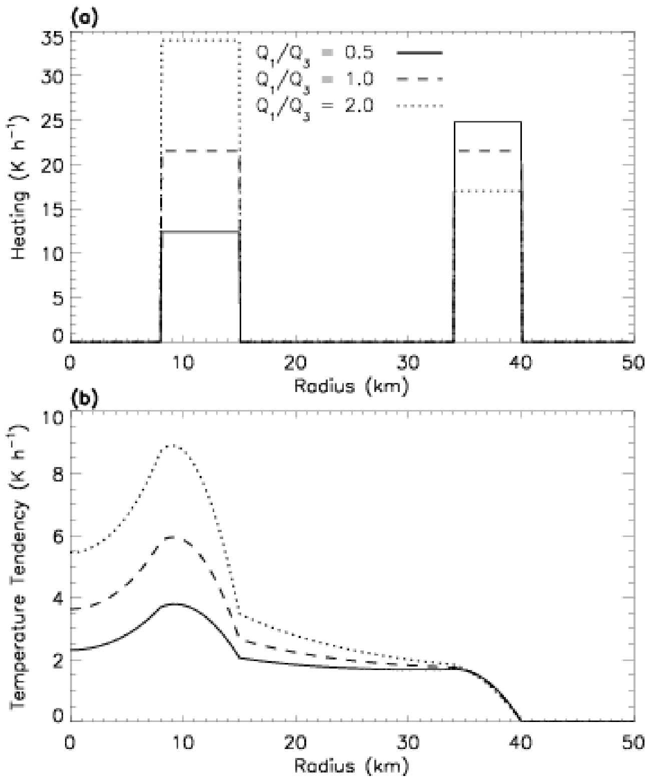

Figure 2. (a) Idealized radial profiles of the diabatic heating during the collapse of the inner eyewall. The dotted line ($Q_1/ Q_3 = 2$) is the early stage, where Q_1 and Q_3 are the diabatic heating associated with the inner and outer eyewall, the dashed line ($Q_1/ Q_3 = 1$) is an intermediate stage, and the solid line ($Q_1/ Q_3 = 0.5$) is the final stage of collapse. (b) Corresponding radial profiles of temperature tendencies.

We have also used our idealized model to investigate changes in the transverse circulation during the contraction and intensification of an outer eyewall. We consider a broad range of wind profiles, which vary over the range of profiles shown in Fig. 3a. Thus, inertial stability increases within the shrinking moat and outer eyewall as the outer eyewall contracts inward. Because the area-averaged diabatic heating is fixed, the diabatic heating rate in the outer eyewall increases as the outer eyewall contracts inward. This facet is reflected in the vertical motion fields (Fig. 3b). The most noteworthy result of this experiment is the rapid increase in subsidence within the moat (and eye) as the outer eyewall moves inward and intensifies. Increasing temperature tendencies (Fig. 3c) similarly reflect the enhanced subsidence that occurs as the contraction occurs. These results suggest that it is not surprising that eye-like conditions are observed in the moats of storms with mature concentric eyewalls (e.g., Houze et al. 2007). In regards to the storm’s ability to efficiently maintain a centralized warm core, the computed temperature tendencies imply that an intensifying outer eyewall counteracts the deleterious impacts of shifting diabatic heating from the inner to the outer eyewall. Repeating our eyewall replacement cycle calculations, but neglecting increases in inertial stability, we find little change in moat and eye subsidence as the outer ring of diabatic heating contracts inward. Therefore, these results suggest the primary factor controlling enhanced moat and eye subsidence is the increasing inertial stability associated with a strengthening outer eyewall.

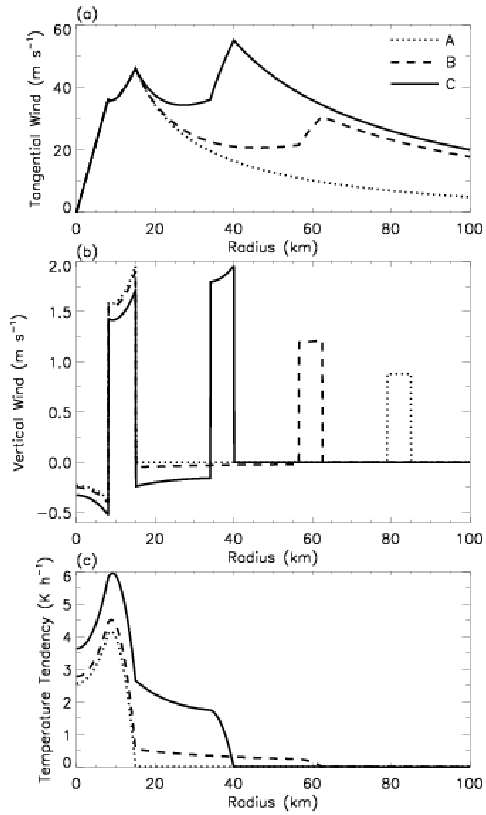

Figure 3. Radial profiles of (a) tangential wind (m s^{-1}), (b) the radially-dependent part of the log-pressure vertical velocity (m s^{-1}), and (c) the radially-dependent part of the temperature tendency for three different cases during a hypothetical eyewall replacement cycle.

Because our simple model does not contain a frictional planetary boundary layer, we cannot adequately address the impact of concentric eyewalls on low-level inflow and the radial moist entropy flux. Therefore, we are currently applying numerical solvers to explore more generalized transverse circulation equations that account for a frictional boundary layer. This approach also allows for a more general study of the baroclinic structure of the cyclone on concentric eyewall cycles. We would like to study whether an upper level warm core has a larger stabilization effect on the convection in the inner eyewall than it does on the convection in the outer eyewall.

Finally, the idealized approach using the Eliassen transverse circulation equation is, of course, restricted by its neglect of asymmetries, which are hypothesized to play a critical role in secondary eyewall formation (e.g., Montgomery and Kallenbach 1997; Kuo et al. 2004, 2007). We are currently studying high resolution, full-physics, three-dimensional WRF simulations of tropical cyclones to explore many of the aspects of the axisymmetric models and to determine how asymmetries affect such results.

b) Empirical/statistical results

Under a separate NOAA-funded project, and with earlier contributions from personnel at the Naval Research Laboratory, we have just completed the construction of a large and unprecedented database of secondary eyewall formation (SEF) occurrences. This required a comprehensive study of available

microwave satellite imagery (archived at the NRL), radar imagery, and various aircraft reconnaissance and land-based reports. Our new database contains over 300 cases of SEF globally, with the majority occurring in the Western North Pacific. For this ONR project, our goal is to identify environmental features that are significantly related to SEF, with an emphasis on Western North Pacific tropical cyclones, and apply these conditions to the initialization of the numerical simulations. Once an SEF event takes place, the subsequent evolution of storm structure and intensity depends crucially on whether the storm undergoes an eyewall replacement, or becomes an annular storm. During this phase of our empirical study, we are particularly interested in identifying environmental differences between the two possible post-SEF evolutions. A second goal of our empirical/statistical study is to ultimately construct objective algorithms that will skillfully diagnose SEF in an operational setting. We’ve made significant headway toward each of these two goals in the past year, as partially outlined below.

At this early stage following the completion of the SEF database, we have identified a number of environmental features that relate significantly to SEF. These include the amplitude and meridional structure of the ambient SST anomalies, low-level and mid-level moisture, vertical wind shear, and lapse rates, among others. To identify these environmental features, we have performed composite analyses that were then subjected to statistical significance tests. Additionally, Principal Component Analysis was applied to the database and the expansion coefficients of the leading modes of environmental variability were stratified by cases of SEF, and tested for statistical significance.

We’ve applied these features in a Bayesian classification framework that combines climatological probabilities of SEF with “class conditioned” probability density functions for the environmental features. Here, we have 2 classes (binary classification). Class 1 comprises tropical cyclone fixes with intensity greater than 100 kt, but no SEF occurred in the following 12 hours. Class 2 comprises the sample of cases where SEF did occur within 12 hours. The Bayesian classifier provides probabilities that a particular group of features belongs to a particular class. The figure shows how much additional skill beyond climatology is gained with the inclusion of the feature matrix. The climatological probability of SEF occurring is 26% based on simple historical counts. This is what we would always predict if we had no other information. With the inclusion of the feature matrix, we correctly predict, on average, significantly higher probabilities in class 2 and lower probabilities in class 1, as desired.

A very intriguing recent result uncovered in the empirical portion of the project is that subsidence near the storm center appears to be systematically greater in the SEF cases. This is nicely reconcilable with the theoretical concepts outlined above, namely that the increased inertial stability related to the outer eyewall increases local subsidence by constraining the local radial flow. We are looking more deeply into this relationship at the moment.

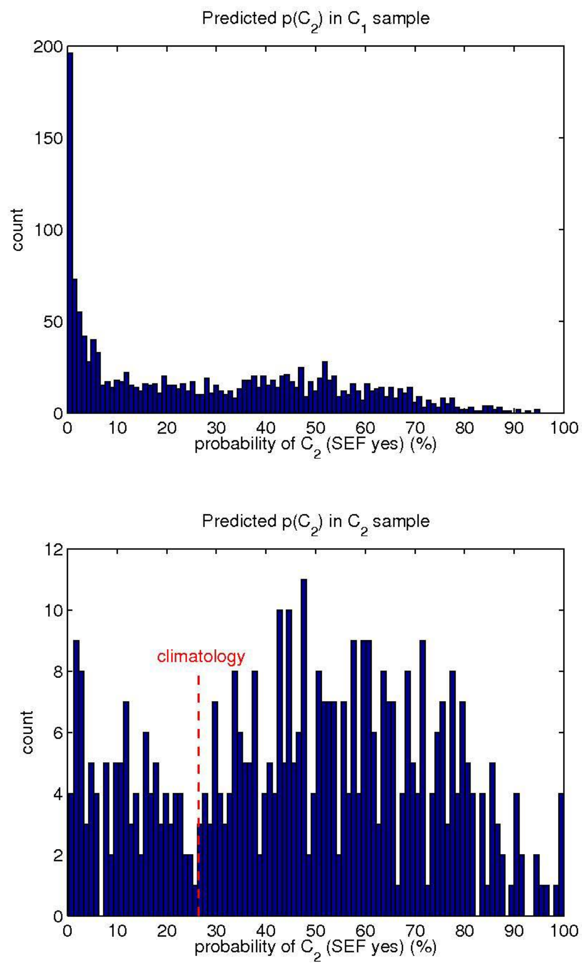

Figure 4. Distribution of predicted probabilities that SEF will occur within the next 12 hours. Top panel: cases when SEF did not occur (Class 2 sample). Bottom panel: cases when SEF did occur (Class 1 sample). All points to the right of climatology in the bottom panel represent cases where the feature matrix provided useful information. When the total sample is considered, the environmental features provide measurable skill.

IMPACT/APPLICATIONS

Our theoretical and idealized modeling results are uncovering the relevant dynamics of the tropical cyclone transverse circulation as it relates to the presence of secondary eyewalls. We expect this to provide invaluable guidance for initializing the full-physics numerical simulations that will be continued during the second year of this project. In addition to providing further guidance for numerical simulations, the Bayesian classifier provides an objective algorithm that has excellent potential for future transition to operations.

RELATED PROJECTS

As noted, much of the database construction required for the empirical/statistical part of this project was performed by a Ph.D. student under an active NOAA grant (P.I. Kossin).

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